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Laser Transmitters for 70-MHz Entrance Links

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Lightwave transmitters providing an amplitude-modulated light output from injection lasers have been designed and tested. Six transmitters were assembled using GaAlAs double-heterostructure lasers and displaying (i) third-order intermodulation products >26 dB below the fundamental at 80-percent modulation index and 0.6 to 0.8 mW average optical output; (ii) excess noise ratios <1.5 dB; and (iii) frequency response within ±0.6 dB from 0.1 to 100 MHz. These transmitters were burned-in at room temperature for 300 h and used with entrance links in a satellite experiment.

I. INTRODUCTION

An experiment to evaluate lightwave technology as a means for providing inexpensive, wideband, reliable entrance links between remote satellite earth stations and video/telephone operating centers is being performed at Bell Laboratories locations at Holmdel, N.J. and Naperville, Ill.[1] In this experiment, either light-emitting diodes (LEDs) or injection-laser diodes (ILDs) are intensity-modulated with a 70-MHz electrical signal that is frequency-modulated by baseband signals (IM/FM). Analog receivers using either p-i-n photodiodes or avalanche photodiodes (APDs) convert the modulated light back into electrical format. The frequency-modulated 70-MHz carrier occupies the band 70 ± 20 MHz. There is also a possibility of sending several narrowband FM carriers occupying the same band. The baseband signal would be either a single 6-MHz diplexed TV channel or 1200 multiplexed voice channels occupying a similar bandwidth. Others have also reported the application of fiber optics to satellite entrance links.[2,3]

The design objective for the transmitter was to achieve a carrier-to-noise ratio(CNR) of at least 35 dB. If an injection laser were used as the source, a simple analysis of signal-to-noise ratio showed that, to meet this requirement, an average power of −10 dBm must be launched into the optical fiber.[4] This assumes 50-percent modulation index, 10 dB of

fiber and connector loss, 10-dB excess noise from the laser, and a p-i-n photodiode as a detector. The receiver amplifier is of the transimpedance type with a transimpedance of 4 kΩ and a noise resistance of 2 kΩ. Because of the large laser excess noise assumed in this analysis, the use of an APD would not improve the receiver sensitivity. A launched power level of −10 dBm can be easily met using injection lasers. On the other hand, if an LED were used as a source and an APD as a detector, the required power level would be −15 dBm. Burrus-type LEDs can easily meet this requirement. For a single-carrier signal, distortion arising from nonlinearities in the lasers or photodetectors is relatively unimportant. However, for a multi-carrier signal, distortion products will have the same effect on the FM detection process as noise, and thus the sum of noise and distortion must be kept 35 dB below the carrier level. The linearity requirements could be met using *selected* injection lasers and Burrus-type LEDs, although the distortion may increase with aging in the case of lasers.[5] Nevertheless, it was decided to use lasers as sources because they could launch much larger power into the fiber and because of their long lifetimes.[6]

This paper first describes the transmitter design, including circuitry and packaging. Next, intermodulation (IM) distortion and excess-noise measurements on the transmitters are presented. Finally, observations of transmitter performance during burn-in are described.

We designed and assembled nine analog transmitters using 12-μm stripe, GaAlAs double-heterostructure injection lasers.[7] These transmitters were burned-in for 300 hours and six of the nine were used for the field experiment. The receivers, not described in this paper, were equalized versions[8] of a previous design,[9] with a response of ± 0.1 dB from a few kilohertz to 100 MHz.

II. TRANSMITTER CIRCUITRY AND PACKAGING

An injection laser is a threshold device with a light-current (L-I) transfer characteristic as shown in Fig. 1. Below threshold, light output is spontaneous LED light. Above threshold, the light is a coherent, lasing output. For analog modulation, the laser clearly must be biased above threshold, for example at point B in Fig. 1, in the center of a linear lasing region. The optical output then follows amplitude variations in the device current.

Transmitter design is complicated, however, by the fact that the threshold, and hence the operating point, are strong functions of temperature and device aging. Therefore, the operating point B must be stabilized under feedback control of some sort.

A digital circuit previously designed incorporating such feedback control[10] has been modified for high-frequency analog modulation. The modified circuit consists of two distinct parts: the driver and the

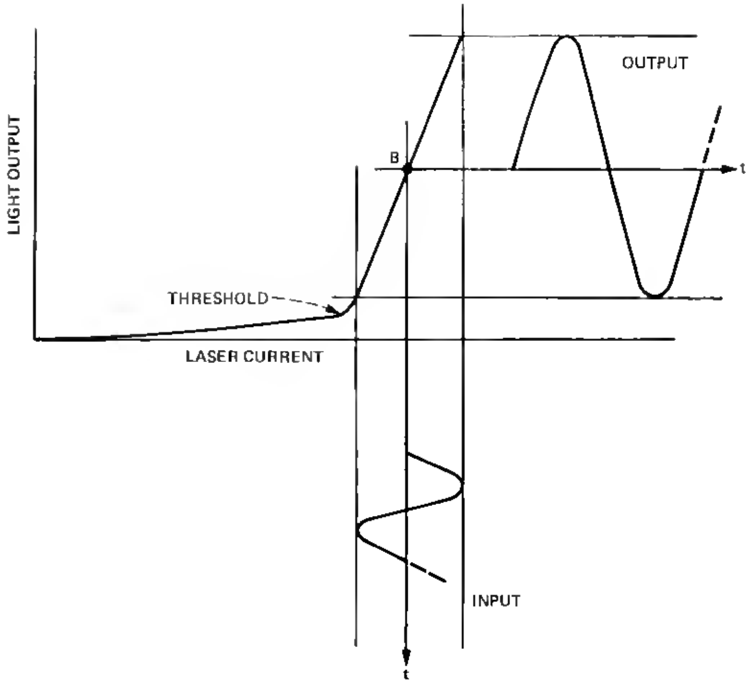

Fig. 1—Analog modulation of an injection laser.

feedback control itself (see Fig. 2). The driver is a one-transistor circuit which converts the input signal voltage to a collector current which flows through the laser. Voltage measured across the 10 Ω emitter resistor of Q_1 at a test point allows monitoring of the modulation current. The frequency response of the modulated light output using this driver was within ±0.6 dB from 0.1 to 100 MHz. The second- and third-order intermodulation products in the drive current were at least 42 dB and 52 dB respectively, below the fundamental. Thus it is seen in the next section that the distortion of the circuit can be ignored in comparison with distortions arising in the laser.

An optical-fiber tap[11] samples the average optical output for feedback control. In a standard closed-loop configuration, the laser bias is controlled so as to maintain the level of this sample constant on a 3-ms time scale. Therefore, the bias does not change in response to modulation of frequencies above 300 Hz, but does limit the low-frequency response of the transmitter. (Experiments have shown, however, that the time constant can be made much longer so that frequency response is attainable down to tens of hertz.)

The laser was mounted in a hermetically sealed package.[12] The laser emission was coupled through a pigtail fiber with a hemispherical lens

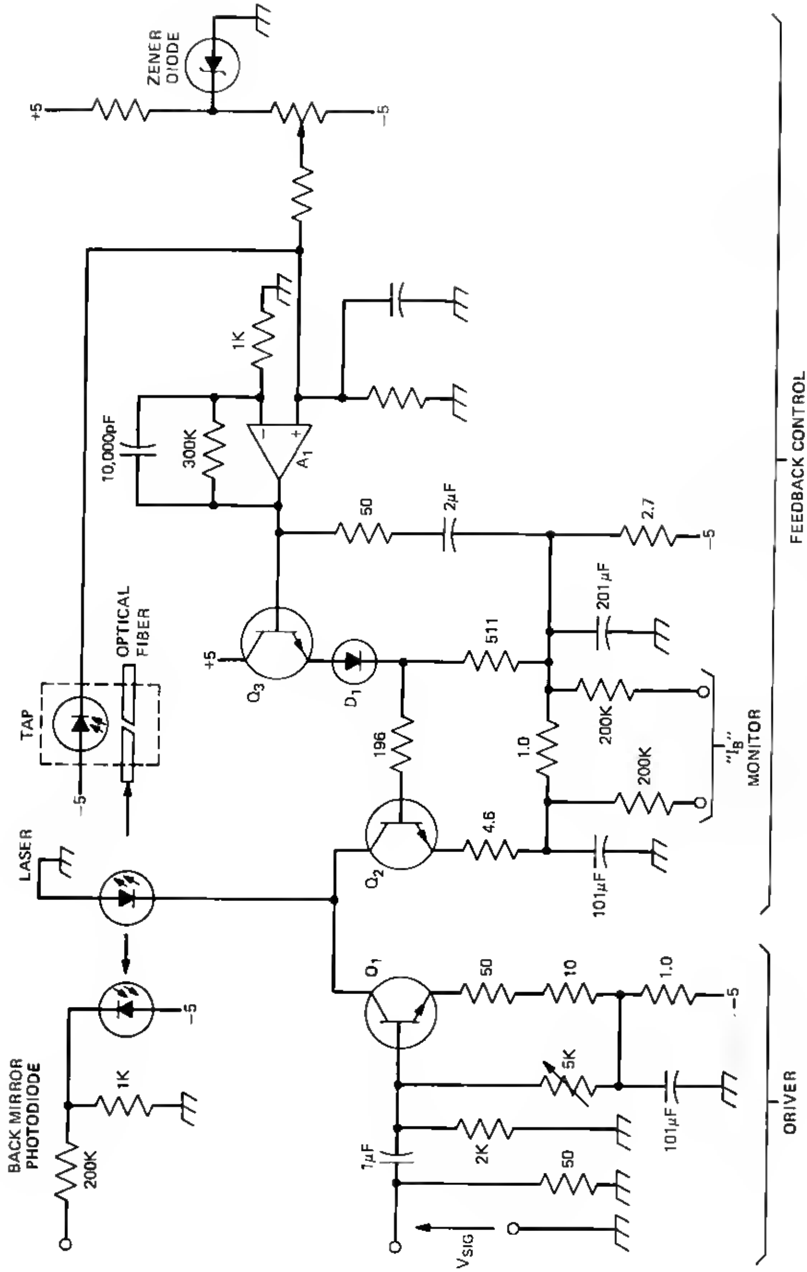

Fig. 2—Laser transmitter circuit.

at its tip to improve the coupling efficiency (about 30 to 50 percent). The optical tap in the pigtail assembly diverted about 10 percent of the power in the fiber to a p-i-n photodiode for controlling the laser operating point. There was also a p-i-n photodiode in the package for monitoring the back-mirror laser emission. The laser package and the electronic circuits were mounted on a printed-circuit board.

III. INTERMODULATION DISTORTION

Intermodulation products were measured by applying two signals of equal amplitude at frequencies $f_1 = 25$ MHz and $f_2 = 30$ MHz to the laser through a transistor driver (Q_1 in Fig. 2). The laser was dc-biased to emit 2 mW of optical power from its front mirror (P_{FM}) although, infrequently, measurements were made at higher average power levels. The modulated light was detected using a p-i-n photodiode and its output power was measured with a spectrum analyzer. The fundamental power, either f_1 or f_2 components, one of the second-order products $f_1 + f_2 = 55$ MHz, and one of the third-order products $2f_2 - f_1 = 35$ MHz were measured as a function of modulation index m. Intermodulation products from the laser could be measured to about 50 dB below either f_1 or f_2 components (56 dB below the sum of f_1 and f_2 components) using this apparatus. Results for one laser having a fairly linear $L-I$ characteristic are shown in Fig. 3, where V_{sig} is the peak input signal voltage per tone to the transistor driver. One notices that, at $P_{FM} = 2$ mW (shown in solid lines), the fundamental component (either f_1 or f_2) of the output power of the photodiode is increased by 6 dB, the second-order component by 12 dB, and the third-order component by 18 dB as V_{sig} is doubled. This is typical of a nonlinear transfer charactistic that can be expressed as a Taylor series. This relationship did not hold at $P_{FM} = 3$ mW (shown in broken lines) where a large swing of V_{sig} extended to a region of greater $L-I$ nonlinearity.

The second-order components can be excluded from the useful band by choosing a proper frequency-multiplexing scheme. However, the third-order components fall within the band and they degrade the effective CNR. From Fig. 3, the third-order component ($2f_2 - f_1$) at $m = 0.8$ was 37 dB below the f_1 component; therefore, the carrier-to-distortion ratio (CDR) is $10 \log P(2f_2 - f_1)/2P(f_1) = 42$ dB. The largest third-order products are of the form $f_1 + f_2 - f_3$ and are 6 dB larger than the type $2f_2 - f_1$.[13] Thus the worst CDR of the distortion products of this laser would still be 37 dB, exceeding the requirement for the multicarrier FM applications (35 dB). However, the uncertainty in the aging behavior of these lasers makes them less suitable for these applications. It has been observed that nonlinearities in the $L-I$ characteristic are not always stable over extended periods of time.

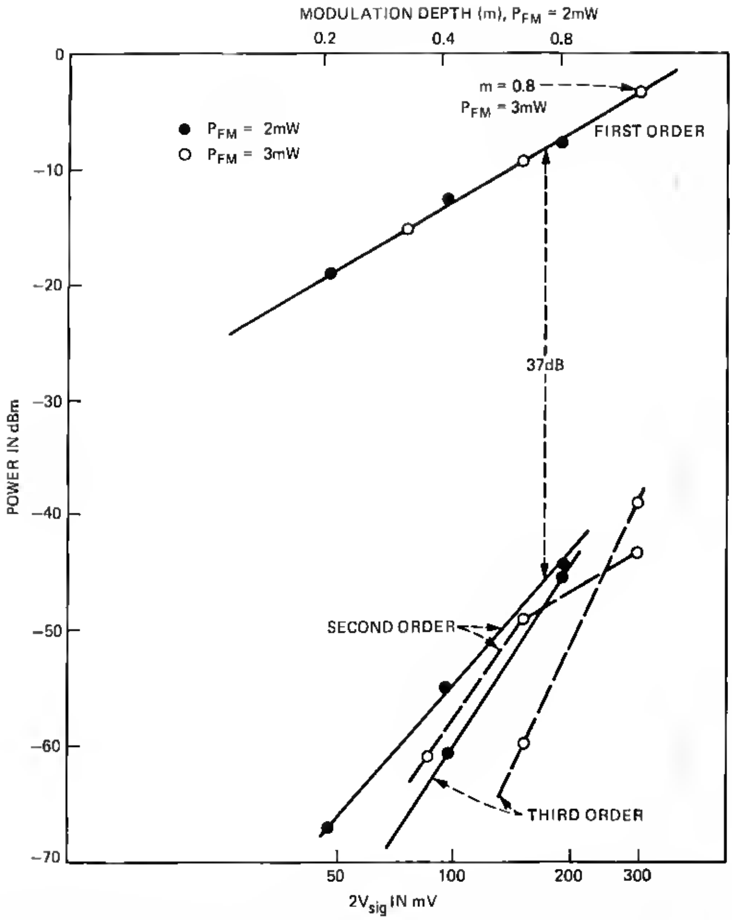

Fig. 3—Fundamental, second-, and third-order intermodulation components vs 2 V_{sig} at $P_{FM} = 2$ mW and 3 mW for a 12-μm stripe laser. V_{sig} is the peak input voltage per tone to the transistor driver. The slopes of the lines are 6 dB/octave, 12 dB/octave, and 18 dB/octave. Modulation depth m is also shown.

Both the severity of a nonlinearity and its position on the $L-I$ characteristic can change during periods of hundreds to thousands of hours.[14]

For other 12-μm stripe lasers with various degrees of nonlinearity in their $L-I$ characteristics, the third-order components varied from 17 to 46 dB (average 33 dB) below the fundamental at 2 mW average powers (P_{FM}) and $m = 0.8$.

The second-order intermodulation components of these lasers varied from 16 to 40 dB (average 29 dB) below the fundamental at $P_{FM} = 2$ mW and $m = 0.8$.

Intermodulation products from a linear 8-μm stripe laser[15] were also measured for average powers up to 5 mW. The results are shown in Fig. 4. The distortion for a given depth of modulation improved as the average laser power was increased. At 2.5 mW and $m = 0.8$, the third-order products were about the same as for linear 12-μm stripe lasers (~40 dB below fundamental).

Intermodulation products from a strip-buried-heterostructure (SBH) laser[16] were also measured. At an average power of 4 mW and $m = 0.8$, the third-order component was down by about 48 dB. Further improvement in the sensitivity of the measuring setup is necessary to determine such small distortion more accurately. In addition to having a linear $L-I$ characteristic extending up to 100 mW/mirror under pulsed

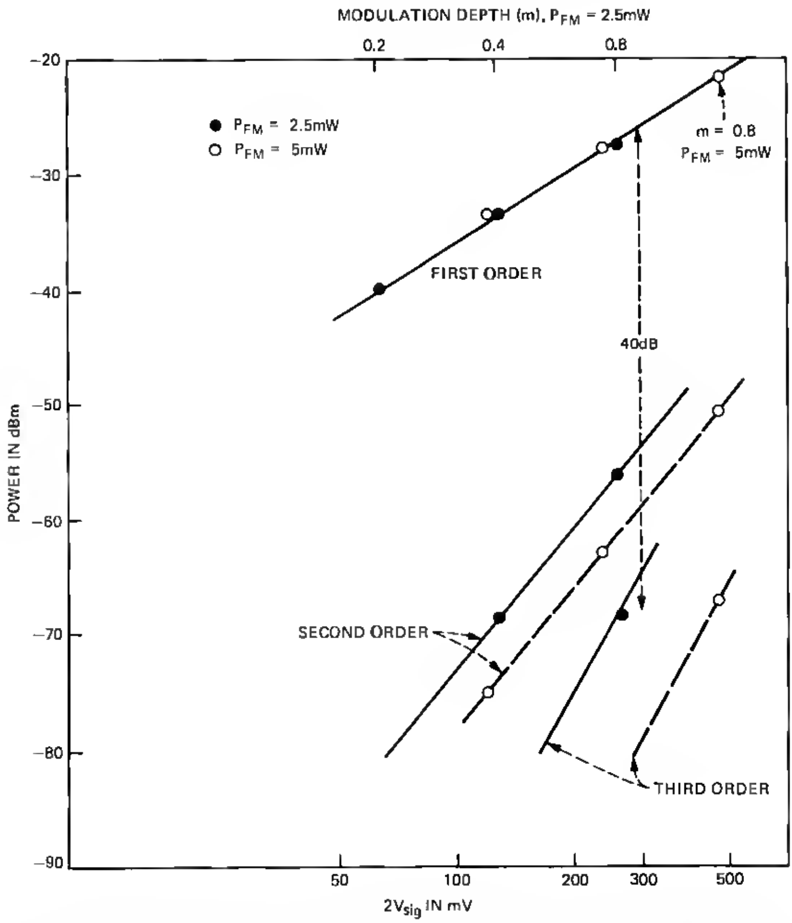

Fig. 4—Fundamental, second-, and third-order intermodulation components vs 2 V_{sig} at P_{FM} = 2.5 mW and 5 mW for an 8-μm stripe laser. Modulation depth m is also shown.

conditions, the SBH laser also has the advantages of a narrowbeam divergence and a single longitudinal mode of operation. Thus, it is well suited for applications requiring amplitude modulation.

IV. EXCESS NOISE

Since the laser is a regenerative amplifier saturated by spontaneous emission noise, the noise present in its output intensity rises above the shot-noise level near threshold and, ideally, it falls back to the shot-noise level above threshold. This excess-noise behavior has been observed in some junction lasers,[17] but in others, especially those with nonlinear $L-I$ characteristics, excess noise persisted above threshold. Since most of our lasers showed some degree of nonlinearity, we measured the noise behavior of these lasers as part of a process before packaging.

The excess-noise ratio is defined as the ratio of intensity noise from the laser to the shot noise expected for the same average photocurrent. (This was called relative-noise ratio in Ref. 17.) Since the noise from an injection laser is known to be independent of frequency from a few megahertz up to its resonance frequency near 1 GHz, the noise was measured at 30 MHz using the apparatus shown in Fig. 5. First, the total power emitted from the front mirror of the laser (P_{FM}) was measured as the drive current was increased. The output voltage of the p-i-n photodiode packaged with the laser to monitor the emission from the back mirror (V_{BM}) was recorded at discrete levels of P_{FM}. This measurement provided sufficient data to infer P_{FM} from the back-mirror signal, even in the presence of drift in threshold. Next, the laser was driven in its LED regime (P_{FM} = 0.2 mW) and the front-mirror

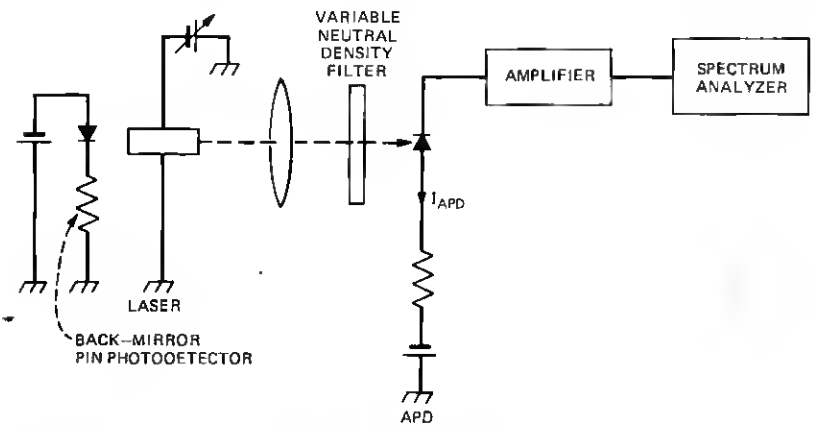

Fig. 5—Diagram of the apparatus used to measure excess noise from the junction laser.

emission was focused through a neutral-density filter onto an APD. The APD output was amplified and measured with a spectrum analyzer. The spectrum analyzer measured the sum of the avalanche-multiplied noise from the laser light and the dark current from the APD and the thermal noise from the amplifier. The noise from the latter was at least 15 dB below the other noise sources. Thus the amplifier thermal noise could be neglected in calculating the excess-noise ratios. The drive current to the laser was then increased, and, at discrete levels of P_{FM}, the neutral-density filter was adjusted to attenuate the optical signal until the average photocurrent of the APD (i_{APD} in Fig. 5) was the same as that when the laser was driven as an LED. The difference in noise power (expressed in dBm) read off the spectrum analyzer is the excess-noise ratio in decibels.

The excess-noise ratios of two lasers, one with a linear and the other with a nonliner $L-I$ characteristic, are shown in Fig. 6. The excess noise peaked near lasing threshold. A small secondary peak appeared near the power level where the $L-I$ characteristic became nonlinear, similar to what has been observed by others.[17, 18] Many lasers selected for this experiment showed fairly linear $L-I$ characteristics up to $P_{FM} = 4$ mW, and no secondary noise peak was observed within this power level. For the 17 lasers measured, the excess-noise ratio decreased to less than 1.5 dB when the lasers were driven at $P_{FM} = 2$ mW (the average power for all the packages). However, with a large modulation index (≈ 0.8), the laser will be driven down toward threshold for a fraction of a modulation cycle, and more excess noise will be added to the system during this period. How this effect will influence the overall system performance is not clear at this time.

V. BURN-IN RESULTS

Nine lasers were selected for packaging based on their relatively low IM distortion, small excess-noise ratios, and absence of severe kinks in their $L-I$ characterstics at both mirrors below $P_{FM} = 4$ mW.

All completed packages were mounted in a life-test rack and operated for 300 h at room temperature (18 to 26°C). The photocurrents of the p-i-n diode in the tap, the p-i-n diode in the laser package monitoring the back laser mirror, and a third p-i-n diode monitoring the actual fiber output were monitored. In addition, the drive and bias currents were recorded semiautomatically in a digital format during burn-in. The percent changes of the output power from the fiber ($\Delta P_{fiber}/P_{fiber}$), of the back-mirror p-i-n voltages ($\Delta V_{bm}/V_{bm}$) and the bias current (I_B) are shown in Table I, together with the second- and the third-order intermodulation products and excess-noise ratios measured at $P_{FM} = 2$ mW. Among the nine packages completed, six showed less than 2-percent change in the bias current (I_B) during burn-in. Part

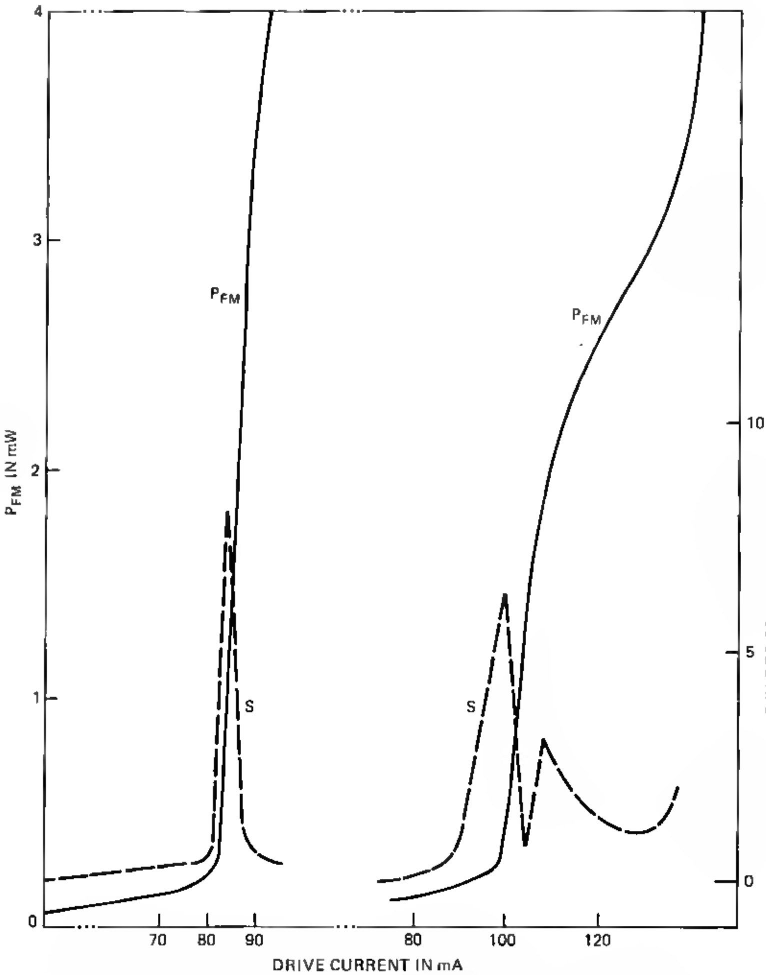

Fig. 6—Laser power (P_{FM}) and the excess-noise ratio (S) vs drive current.

of the change in I_B was due to variations in the ambient temperature and is not necessarily indicative of deterioration of the lasers. Consequently, they were used in the field experiment.

One package (L—2) developed large changes in fiber output, back-mirror emission, and bias current, while the tap photocurrent was kept constant by the feedback circuit. The cause of this instability was probably mechanical instability in the tap. The remaining two packages failed in less than seven hours for unknown reasons.

Table I—Results of 300 h burn-in at room temperature, and second- and third-order intermodulation products and excess noise ratios at P_{FM} = 2 mW

Package No.	$\frac{\Delta P_{fiber}}{P_{fiber}}$ (±%)	$\Delta V_{BM}/V_{BM}$ (±%)	I_B (mA)	2nd-order inter-modulation (−dB)	3rd-order inter-modulation (−dB)	Excess-noise ratio (dB)
L-1	2	5.3	82–84	38	26	1.2
L-2	7.5	8.6	80–89	32	17	1.1
L-3	1.4	2.6	97–101	31	40	0.8
L-4	0.8	1.1	76–78	34	46	1.5
L-5	1.4	10.2	86–87	29	34	1.3
L-7	1.2	1.9	110–112	20	35	1.4
L-9	1.8	2.1	83–85	16	30	0.1

VI. SUMMARY AND DISCUSSION

Lightwave transmitters capable of delivering frequency-modulated subcarrier IF signals (70 MHz ± 20 MHz) were developed for use in satellite entrance links. Double-heterostructure GaAlAs injection lasers with 12-μm stripes were used. At 2-mW laser power, the excess-noise ratio from the lasers was not more than about 1.5 dB. Second-order IM products were 16 to 40 dB and third-order IM products were 17 to 46 dB below the fundamental at a modulation index of 0.8. The average power coupled into the FT3 fiber (NA = 0.23 core dia = 55 μm) varied from 0.6 to 0.8 mW.

The third-order IM products observed for many 12-μm stripe lasers were sufficiently low for possible applications in multi-carrier transmission. However, the magnitude of distortion may increase as the lasers age, since they tend to develop nonlinearities in their *L-I* characteristics. In principle, improvements in reducing the nonlinear distortion from direct modulation of injection lasers can be approached from two directions: electronic compensation for the nonlinearity and/or modification of the laser structure. Use of a predistorted signal derived from one laser and applied to a second laser[19] to minimize the distortion products has been successful with LEDs, but it may be difficult with injection lasers since two lasers cannot be expected to develop the same nonlinearity at the same time. The approach using improved laser structures has been more successful. Already various structures have been reported in the literature[16,20–22] showing extremely linear characteristics. With these new, linear structures, ultimately the magnitude of the IM products and the useful bandwidth for analog modulation will be determined by the inherent resonance of these lasers, which is in the vicinity of 1 GHz. Due to these resonances, distortion would be expected to appear at subcarrier frequencies of

several hundred megahertz even for a laser with perfectly linear L-I characteristics[23] as measured at dc (or low frequencies).

VII. ACKNOWLEDGMENTS

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